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Research paper

Correlations between the North China Craton and the Indian Shield: Constraints from regional metallogeny

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A B S T R A C T

The correlation between the North China Craton (NCC) and the Indian Shield (IND) has been a hot topic in recent years. On the basis of ore deposit databases, the NCC and IND have shown broad similarity in metallogenesis from the middle Archaean to the Mesoproterozoic. The two blocks both have three major metallogenic systems: (1) the Archaean BIF metallogenic system; (2) the Paleoproterozoic Cu-Pb-Zn metallogenic system; and (3) the Mesoproterozoic Fe-Pb-Zn system. In the north margin of the NCC and the west margin of the IND, the Archaean BIF-Au-Cu-Pb-Zn deposits had the same petrogenesis and host rocks, the Paleoproterozoic Cu-Pb-Zn deposits were controlled by active belts, and the Mesoproterozoic Fe-Pb-Zn deposits were mainly related to multi-stage rifting. Matching regional mineralization patterns and geological features has established the continental assembly referred to as "NCWI", an acronym for the north margin of the NCC (NC) and the west margin of the IND (WI) during the middle Archaean to the Mesoproterozoic. In this assembly, the available geological and metallogenic data from the Eastern Block and active belts of NC fit those from the Dharwar craton and the Aravalli–Delhi–Vindhyan belt of WI, respectively. Moreover, the depositional model and environment of Paleoproterozoic metasedimentary manganese deposits in NCWI implied that the assembly may be located at low latitudes, where the conditions were favorable for dissolving ice and precipitating manganese deposits.

1. Introduction

The early Precambrian connection of the North China Craton (NCC) with other cratonic blocks has been a subject of debate in the past decade (Wilde et al., 2002; Hou et al., 2008a). Qian (1997) and Wilde et al. (2002) believed that the NCC and the Baltic Shield may have once been connected in terms of age, lithologies, and configurations of the Archaean and Palaeoproterozoic active belts. However, the main cratonization time or amalgamation time of the micro-continental blocks of the Baltic Shield was between 2.8 and 2.6 Ga, whereas the growth and stabilization of the granite–greenstone belt was from 2.7 to 2.6 Ga (Amelin et al., 1995; Artemieva, 2006; Hou et al., 2008b). These values are significantly different from those of the NCC, in which the cratonization of micro-continental blocks began at 2.6 to 2.5 Ga and was finally completed at ~1.85 Ga (Zhao et al., 2002, 2005; Kusky et al., 2007; Zhai, 2010). In addition, the palaeomagnetic studies by Elming (1994, 2001) suggested that the Ukrainian Shield did not separate from Fennoscandia until 1.3 Ga. This result contradicts the previous belief that the NCC was adjacent to the Baltic Shield.

Alternatively, Li et al. (1996), Condie (2002), and Wang (2010) proposed that the NCC was once connected to Siberia during the Palaeo- and the Mesoproterozoic based on similarities of Palaeo- to Mesoproterozoic stratigraphy between North China and Siberia. Additionally, some paleomagnetic data appear to support this North China-Siberia connection (Halls et al., 2000; Zhang et al., 2000). However, it remains unknown whether or not this

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connection can be extrapolated to the Archaean, because there are some striking differences in tectonic evolution during the Archaean between the two continental blocks. For example, the Aldan Shield in Siberia first reached stabilization at ~3.1–2.9 Ga, and the micro-continental blocks of the Anabar Shield were amalgamated at 2.6 to 2.5 Ga (Nutman et al., 1992; Rosen et al., 2006). These data are significantly different from those of the NCC during the Archaean.

Zhao et al. (2003a) made a comparison of sedimentary sequence, isotopic geochronology, lithology, tectonics and geochemistry between the NCC and the IND. He suggested that the eastern Block (EB) of the NCC and South Block (SB) of the IND were once connected. A possible fit was proposed for the reconstruction of the EB and SB. In this reconstruction, the northern margin of the EB was placed adjacent to the western margin of the SB, with the Trans-North China Orogen (TNCO) and the Western Block representing the continuations, respectively, of the central Indian Tectonic Zone (CITZ) and the North Indian Block. Hou et al. (2008a) argued that the NCC, IND and Laurentia were part of Columbia prior to its extension and break up on the basis of the ca. 1.85–1.75 Ga giant radiating dyke swarm and Large Igneous Provinces (LIPs). Zhao et al. (2011) thought that the present south margin of the NCC represented an active continental margin in Columbia and was likely to face an open ocean, whereas its north margin was connected to a large landmass based on subduction-related accretion at the NCC margins.

However, most of the aforementioned studies are based on comparisons of geological characteristics, and it is generally accepted that ore deposits are not randomly distributed in time and space and are closely related to geological evolution (Qiu et al., 2014). Zhai (2010) and Zhai and Santosh (2013) argued that the metallogenesis has a high spatiotemporal coupling with major geological and tectonic events in Earth's history. Mao and Zhong (2001) argued that similar geological evolution and metallogenic geological conditions correspond to similar metallogenesis, including similar mineralization types, mineralization characteristics and ore-forming processes. In this paper, we further test and extend Zhao's (2011) hypothesis by comparing the Archaean to Palaeoproterozoic metallogenic systems of the NCC and the IND. Our study reveals that the NCC and the IND show strong metallogenic similarities from the middle Archaean to the Mesoproterozoic. The conclusions verify the tectonic affinity between the NCC and the IND, supporting that the north margin of the NCC and west margin of the IND once connected during the middle Archaean to the Palaeoproterozoic era. In addition, the depositional environment of the Paleoproterozoic metasedimentary manganese deposits of the two blocks implied that the assembly may have been located at low latitudes. In contrast to the NCC, the IND was likely to have been located at lower latitudes, where the conditions were more favorable for dissolving ice after the "Ice Earth" (2.5–2.3 Ga) and precipitating manganese deposits.

2. Geological background

The NCC and the IND are both ancient continental blocks (Fig. 1a). Approximately 90% of the continental crust in the NCC formed in the early Precambrian period. The basement of the NCC consists of variably exposed Archaean to Paleoproterozoic rocks, including tonalite–trondhjemite–granodiorite (TTG) gneisses, granites, charnockites, migmatites, amphibolites, greenschists, pelitic schists, Al-rich gneisses (khondalite), banded iron formations (BIFs), calc-silicate rocks, and marble (e.g., Zhao et al., 1998, 2005; Kusky et al., 2007; Zhai, 2010, 2011; Zhai and Santosh, 2011). The basement is tectonically divisible into the eastern and western Blocks, which are separated by a central zone called the Trans-North China Orogen. This zone is a nearly 1500 km-long orogenic belt that extends from north to south. The Western Block

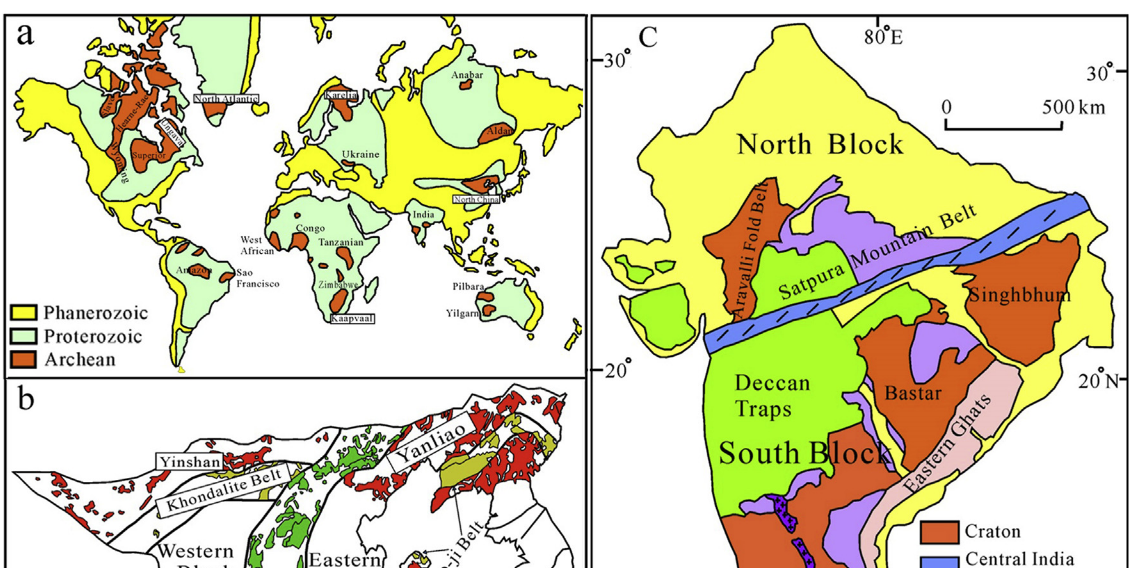

Figure 1. (a) A map of showing the distribution of ancient nuclei and Archaean micro-blocks (revised after Santosh et al., 2009); (b and c) tectonic architecture of the North China Craton and the Indian Shield (b–revised after Kusky et al., 2007; c–revised after Zhao et al., 2002).

can be divided into the Yinshan Block in the north and the Ordos block in the south. The Yinshan and Ordos blocks are separated by a Khondalite Belt, which represents a Paleoproterozoic collisional orogen at approximately 1.95 Ga (Fig. 1b) (Wu and Zhong, 1998; Kusky et al., 2007; Zhao, 2009; Li et al., 2010).

The basement of the IND has a lithology similar to that of the NCC and consists of TTG gneiss, granite, charnockite, argillite, quartzite, calc-silicate, amphibolite rocks, migmatites, and BIFs (Goodwin, 1996; Mohanty, 2011, 2012). The Archaean to Palaeoproterozoic basement in the IND can be roughly divided into two major cratonic blocks, namely the South Indian Block (SIB) and the North Indian Block (NIB), which are separated from each other by a linear orogenic belt called the central Indian Tectonic Zone (CITZ) (Fig. 1c). The CITZ is a Proterozoic mountain belt that has amalgamated the Bundelkh and protocontinent in the north NIB and the Deccan protocontinent (Singhbhume–Bastare–Dharwar) in the south SIB. In addition to these major tectonic units, along the east coast is the eastern Ghats. On the southern tip of India is the southern Granulite Terrain, which is predominantly Proterozoic, but was widely reworked during the Pan-African event (e.g., Zhao et al., 2003a; Zhao, 2009; Mohanty, 2011, 2012).

3. Comparisons of the Precambrian metallogenesis between the NCC and the IND

The NCC and the IND experienced a complex geological evolution since the early Precambrian, characterized by abundant Precambrian solid mineral resources and variable metallogenic mechanisms (Turchenko et al., 2009; Zhai, 2011). We establish a mineralization characteristic database of the NCC and the IND on a scale of 1:50,000,000. This database is an example of the creation of a GIS-oriented database on the geologies and tectonics, isotopic age, and mineralogies of the Precambrian rocks of continents. Based on comparative analyses of the Precambrian metallogenesis between the NCC and the IND, we report the metallogeny characteristics of the NCC and the IND and verify their tectonic affinity.

3.1. Precambrian metallogenesis of the NCC

Precambrian ore deposits were widespread in the NCC (Fig. 2), among which BIF, REE, Pb-Zn, and B-Fe-Mg (magnesite) are especially abundant. Fig. 2 shows that ore deposits of Precambrian age, particularly nonferrous metallic deposits, are widely developed in the northern margin of the craton and TNCO (Shen et al., 2004, 2005; Zhao et al., 2006b; Zhai, 2010).

The six recognized metallogenic zones of Liaodong, Jidong, Wutai-Lvliang, Zhongtiao-Yuxi, Langshan-Daqingshan, and Luxi are based on mineralization types, tectonic units, and geological features. Each zone is accompanied by a spatiotemporal model of tectonic and metallogenic evolution characterized by isotopic dating with various degrees of accuracy. Liaodong is the Fe-Mg-B metallogenic zone, whereas Jidong, Wutai-Lvliang, and Luxi-Jiaodong are the metallogenic zones of BIF–Au. Zhongtiao-Yuxi and Langshan-Daqingshan are the (REE-Fe)–Cu–Pb–Zn metallogenic zones.

During the prolonged tectonic evolution of the NCC, several types of economic ore deposits formed at different times (Table 1). In the early Archaean, ore deposits in the NCC were limited to the supracrustal rocks and gray gneiss as Algoma-type BIF deposits, such as Xingshan in the Caozhuang Group in Jidong (Shen et al., 2005). The Sm-Nd isochron age of plagioclase amphibolite together with the iron ore layer is ~3500 Ma (Jahn et al., 1987). The single zircon U-Pb age of the chrome mica quartzite was >3600 Ma. These isotopic data show that the formation age of the Xinshan deposit was >3500 Ma (Shen et al., 2006).

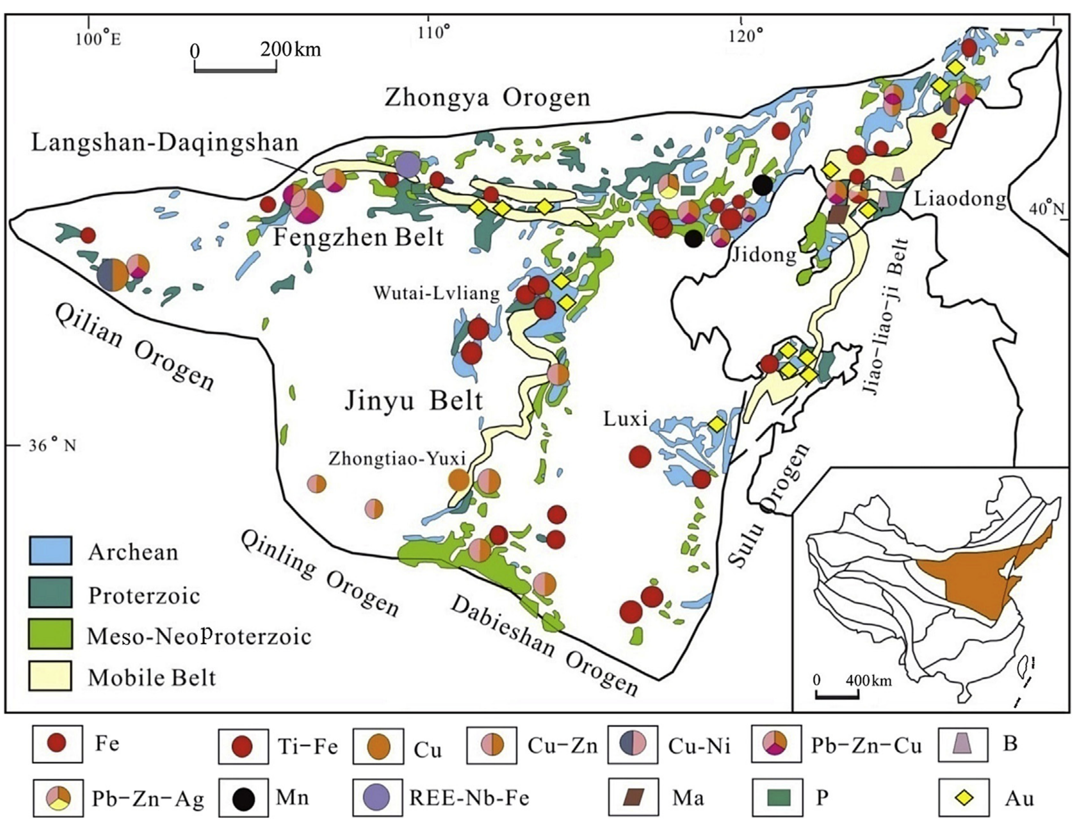

Figure 2. Distribution of major ore deposits in the North China Craton.

Table 1
Precambrian metallogenic characteristics of the North China Craton.

Era (Ga)	Mineral	Metallogenic background	Typical deposit
3.3–2.9	BIF	High-grade metamorphic zone	Xingshan
2.9–2.7	BIF	Greenstone belt, high-grade metamorphic zone	Shuichuang, Qianan
2.7–2.5	BIF	Greenstone belt	Qidashan, Dong-xi Anshan
	Cu-Pb-Zn (VHMS)	Greenstone belt	Hongtoushan
	Au	Greenstone belt	Baizhiyan, Diantou
2.5–1.8	BIF	metamorphic zone	Wutai, Zhuzhangzi, Yuanjiacun
	Cu	Mobile belt	Luojiahe, Henglingguan, Tongkuangyu
	Pb-Zn	Mobile belt	Qingchengzi, Caijiaying
	Cu-Ni	Back-arc basin	Jinchuang
	Mn	Mobile belt	Dashiqiao
	Magnesite	Rift	Qingshanhuai
	B-Fe-Mg	Mobile belt	Houxianyu(B), Wenquangou
	Graphite, Talc	Rift	Nanshu; Fanjiabaozi
	Au	Rift	Baiyun
1.8–1.6	Pb-Zn-Cu (Sedex)	Rift	Dongshengmiao,Huogeqi
	Pb-Zn (MVT)	Rift	Guanshanmen
	Cu (Porphyry, sedimentary)	Rift	Bainaimiao, Tanyaokou
	V-Ti-Fe-P (Magmatic)	Rift	Damiao
1.6–1.3	Mn (Marine sedimentary)	Rift	Dongshuichuang, Wafangzi
	Fe (Sedimentary)	Rift	Xuanhua
	REE-Nb-Fe	Rift basin	Bayan Obo

From 2.9 to 2.7 Ga, due to the global accretionary growth of crust, granite-greenstone and high-grade metamorphic-volcanic rocks were developed in the NCC, such as the Luxi-Liaoji greenstone-TTG belt and the Yanlingguan greenstone belt (Li et al., 2000, 2001; Li et al., 2010; Zhai, 2010). The Algoma-type BIF (e.g., Qian'an and Shuichang) deposits occurred at the Qian'an supracrustal rocks in Jidong, which are mostly in association with metamorphic volcanic rocks (e.g., Shen et al., 2005, 2006; Shi et al., 2010; Zhai, 2010).

From 2.6 to 2.5 Ga, intensive tectonic-metamorphic-magmatic events occurred in the NCC (Shen et al., 1992; Zhao et al., 1993; Kusky et al., 2007; Zhai, 2010). The crust was rapidly accreted during this period, which led to the formation of the Hongtoushan-Dengfeng-Wutai-Anshan-Benxi greenstone belts, accompanied by abundant mineral resources, such as: (1) Algoma-type BIF deposits in the Anshan-Benxi belt (e.g., Qidashan) in Liaodong and the Wutai greenstone belt in Wutai-lvliang (e.g., Shanyangping and Zhuzhangzi) (Shen et al., 2005, 2006); (2) the volcanic massive sulfide (VMS) Cu-Zn deposits (Hongtoushan) in the Hongtoushan greenstone belt in Liaodong; (3) greenstone belt type gold deposits in Jiapigou-Sandaogou in Liaodong, which were extensively reworked in the Mesozoic (e.g., Shi et al., 2010; Zhai, 2010; Zhai and Santosh, 2013).

From 2.35 to 1.8 Ga, the rifting–subduction–accretion-collision occurred and resulted in the development of three major mobile belts: the Jiaoliao active belt in Liaodong in the northeastern NCC (corresponding to the Jiao-Liao-Ji belt), the Jinyü active belt in the central domain (corresponding to the TNCO), and the Fengzhen active belt in Langshan (Fig. 2) (Zhai, 2004, 2010, 2011). During the 2.35 to 2.0 Ga interval, the great oxidation event (GOE) occurred and resulted in an increase of the oxygen and a decrease of the CO_2 contents of the atmosphere. This led to the occurrence of an early cover of shoal-water carbonate sediments, such as the Liaohe Group (e.g., Urban et al., 1992; Chen et al., 1996; Roy, 2000a,b; Condie, 2001; Zhao et al., 2003a; Zhao, 2010). Paleoproterozoic ore deposits were mainly controlled by active belts and affected by the GOE (Zhai, 2010). The Paleoproterozoic orogenic-like metallogenic systems mainly include Cu, Cu–Mo, Cu–Co and Cu–Pb–Zn deposits. These ore deposits, which formed in rift and subducted environments, exhibit orogenic metallogenic characteristics (Sun and Hu., 1993; Geng et al., 2000; Shen et al., 2006; Chen et al., 2009). The Cu–Pb–Zn deposits in the Zhongtiao-Yuxi zone corresponded to metamorphosed VMS deposits (Luojiahe) and were controlled by an active belt. The volcanic-porphyry Cu-Mo deposits were related to accreted arc complexes (Tongkuangyu) (Li et al., 2011). Small-scale Cu-Co ore deposits were related to gabbroic-ultramafic intrusive bodies (Bizigou). The host rocks of the Cu orebodies are the Zhongtiao Group and Jiangxian Group, and the single zircon U-Pb age of host rocks is 2063 to 2166 Ma (Sun et al., 1991; Shen et al., 2005, 2006; Zhai and Santosh, 2013). In addition, geological processes and ore deposits similar to those of the Jinyü active belt also occurred in the lower Liaohe Group in the Jiaoliao belt in Liaodong (Qingchengzi, Caijiaying) (Zhang, 1984; Shen et al., 2006).

As a result of the GOE, boron-bearing felsic volcanics were generated and magnesite-marble and graphite-bearing strata were deposited in rift-related shallow ocean basins. The Dashiqiao Formation hosts the Dashiqiao magnesite deposits related to the rift valley. Zircons from fine-grained felsic gneiss (meta-rhyolite) and a granite vein in the Dashiqiao Formation show ages between 2179 and 2173 Ma (Li et al., 2012). Boron-ore deposits hosted in the fine-grained felsic gneiss occurred in the Lieryu Formation, and sedimentary Pb-Zn ore deposits were developed in the Gaojiayu Formation. A large number of graphite deposits occurred in the Fenzishan Group in the Jiaoliao belt, the Jining Group in the Fengzhen belt, and the upper Lushan Group in the Jinyu belt. In contrast, only minor volumes of superior-type BIF (Yuanjiachun) occurred in the Lanxian Group in Wutai-Lvliang (Zhao et al., 2006a; Wang, 2007; Zhai, 2010; Tang et al., 2012; Zhai and Santosh, 2013).

Mesoproterozoic deposits were mainly controlled by the evolution of the rift trough and the rift valley (Zhai, 2010). The major ore deposits related to the late Paleoproterozoic–Neoproterozoic multiple-rifting events are iron ore deposits, including a vanadium-titanium-iron-phosphate deposit (Damiao ore) in Jidong related to anorogenic magmatism and a REE deposit associated with Nb-bearing iron ores in the Bayan Obo Group (Shen et al., 2005, 2006; Yang et al., 2011; Zhai and Santosh, 2013). In addition, the ca. 1.76 Ga-aged porphyry Mo-Cu deposits (Zhaiwa) in the eastern Qinling Molybdenum Belt in central China possibly formed in a Paleoproterozoic continental arc, which is coeval with the peak eruption period (1.78 to 1.75 Ga) of the Xiong'er Group volcanic rocks (Deng et al., 2013). Mesoproterozoic rifts in Langshan–Daqingshan and Zhongtiao–Yuxi are potential sites of SEDEX–type Pb–Zn–Cu–Fe ore-deposits, such as Dongshengmiao in Langshan and Lanchuan in the west of Henan Province, which are hosted in a sandstone/fine-grained sandstone/calcic fine-grained sandstone sequence and are considered to be related to extensional processes in the NCC (Shen et al., 2005, 2006; Zhao et al., 2006a; Shi et al., 2010; Zhai, 2010; Zhang et al., 2010).

3.2. Precambrian metallogenesis of the IND

The IND is also rich in Precambrian minerals, among which iron, chromium, manganese, copper, lead, zinc and diamond are particularly widespread (Fig. 3) shows that ore deposits of Precambrian age are widely developed in the west margin of the IND and CITZ.

On the basis of metallogenic types, metallogenic epochs, genetic types, tectonic units, and geological features, six metallogenic zones are recognized: Dharwar, Bastar, Singhbhum, Aravalli-Delhi-Vindhyan, eastern Ghats, and lower Himalayas (Fig. 3; Turchenko et al., 2009). Among the foregoing, Aravalli–Delhi–Vindhyan and lower Himalayas are Cu–Pb–Zn metallogenic zones, whereas Dharwar, Bastar, Singhbhum, and Eastern Ghats are metallogenic zones of Fe (Mn), Cr, Au, and Cu–Pb–Zn.

The metallogenic process in IND persisted from >3.2 Ga to the late Precambrian (Table 2). In the early and middle Archaean, the Indian continental nuclei was formed (Sharma, 2009). The rapid

Table 2
Precambrian metallogenic characteristics of the Indian Shield.

Era (Ga)	Mineral	Metallogenic background	Typical deposit
>3.2	BIF	Gneiss-granulite	Churuppa
	Ni-Co-Cr	Gneiss-granulite	Hulk Hill
	Pb-Zn-Cu	Gneiss-granulite	Mamandur
3.2–2.7	BIF	Greenstone belt	Noamundi, Bababudan
	Cr	Greenstone belt	Nuasahi
	Cu	Greenstone belt	Kalyadi
2.5	BIF	Greenstone belt	Bailadila
	PGE	metamorphic zone	Devaranarasipur
	Au	Greenstone belt	Kolar
2.5–1.8	Diamond	Mobile belt	Maghgawan
	Mn-BIF	metamorphic zone	Koduru, Garbham
	Pb-Zn	Mobile belt	Dariba-Raipur
	Cu(U)	Mobile belt	Tamapahar, Narwapahar
	Cu(Mo)	Mobile belt	Malanjkhand
	Cu-Ni	Mobile belt	Ramchandrapahar
	Pb-Zn- (Au) (VMS)	Belt	Rampura-Agucha, Pular-Parsori
1.8–1.6	Pb-Zn-Cu (VMS)	Rift	Saripalli
	Pb-Zn-(Cu) (SEDEX)	Rift	Bageswar
	Cu	Rift	Ganikalawa
	V-Ti-Fe	Rift	Angadibail
1.6–1.3	Barite, REE	Rift basin	Mangampeta, Kodarma
	Cu (Porphyry, sedimentary)	Island arc	Gani-kalawa

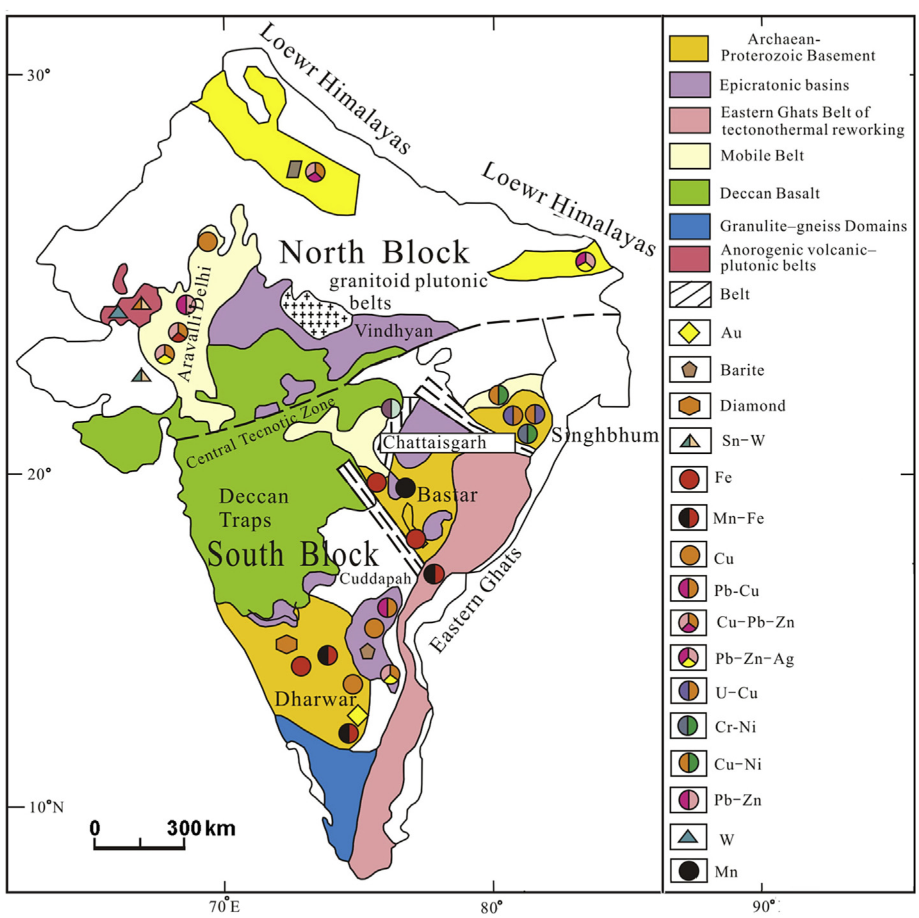

Figure 3. Distribution of major ore deposits in the Indian Shield.

growth of the continental crust led to the extensive formation of gneiss, charnockite, and migmatite, as well as to the accumulation of abundant mineral resources (Goodwin, 1996; Sharma, 2009; Turchenko et al., 2009). Vast reserves of Algoma-type BIF (e.g., Churuppa) occur in the gneiss belts and granulite–gneiss domain in the southern Dharwar Craton, which are closely related to volcano-sedimentary rocks. The VMS metamorphosed Pb-Zn-Cu deposits (e.g., Mamandur), the Ni-Co-Cr (e.g., Hulk Hill) deposits related to ultramafic rocks and the Vairamangalam deposit of muscovite pegmatites occurred in the lower Archaean supracrustal sequences, which metamorphosed under granulite-facies conditions and were incorporated into granite gneisses 3.1 Ga in age. In the Nuggihalli and Holenarasipur structures, which commonly occur at the bottom of green-stone belts, these metasedimentary rocks overlap a layered Cr, Fe, and Ti-bearing peridotite–gabbro–anorthosite complex, as well as the relics of komatiites (e.g., Hussain and Naqvi, 1983; Turchenko et al., 2009; Shi et al., 2010).

In the mid and late NeoArchaean, the continental crust significantly grew and micro-continental blocks were amalgamated, accompanied by large-scale development of greenstone belts and apparent metallogenic processes (Zhao et al., 2003a; Artemieva, 2006; Sharma, 2009; Turchenko et al., 2009). Algoma-type BIF occurred in the Kolar–Ramagiri–Hutti–Maski greenstone belts in the Dharwar Craton, which also contains a large number of greenstone belt type Au deposits (e.g., Karnataka; Kolar) and graphite schists (Kolb et al., 2004; Turchenko et al., 2009; Shi et al., 2010). In the Sargur–Holenarsipur–Nuggihalli schist belts, mafic–ultramafic dunite–harzburgite–gabbro-anorthosite intrusions contain podiform chromite bodies (e.g., Aladahalli). Cu-Zn sulfide occurrences with insignificant Au mineralization are hosted in the mafic schists of the Nuggihalli Schist Belt (Bhattacharya et al., 1990; Turchenko et al., 2009). Some younger Dharwar-type greenstone belts that are characterized by predominantly sedimentary rocks intercalated with volcanic rocks, contain BIF with manganese mineralization (Kodgui). A small amount of Superior Lake-type BIF and some "Sedex" copper polymetallic deposits (Kalyadi) occur in the Bababudan Group. "Sedex" copper polymetallic deposits related to ultramafic-mafic schist are quite rare and very similar to massive sulfide Cu-Pb-Zn ore deposits (e.g., Sivaprakasit, 1980; Arora et al., 1995; Rao and Naqvi, 1997; Du et al., 2009; Turchenko et al., 2009). The Sukma area in Bastar Craton is characterized by a similar mineralization that is rich in BIF (Mn) (e.g., Bailadila). In the Singhbhum Craton, the same mineralization is known in the Noamundi area, with the Joda and Noamundi deposits as typical examples. In addition, the Cr-Ni-Co deposits (Naushahi) related to ultramafic rocks, serpentinites, and talc–serpentine schists occurred in the Sukinda area in the Singhbhum Craton (e.g., Stein et al., 2004; Mondal et al., 2006; Ghosh and Mukhopadhyay, 2007; Alapieti et al., 2008; Turchenko et al., 2009; Shi et al., 2010).

Rifting with violent volcanic activity and intrusion of large amounts of granite occurred in the IND during the Paleoproterozoic, resulting in the emergence of several belts in Central and North India. These belts include rift valleys, such as the Vindhyan–Aravalli–Delhi belt in North India, as well as the Singhbhum Shear zone and the Kotri–Dongargarh fold belt in the Baster Craton (Rao et al., 2005; Sharma, 2009; Mohanty, 2012). The fold belts in the Aravalli–Delhi–Vindhyan (Pb–Zn–Cu) and Singhbhum (Cu–U) Craton are of significant metallogenic interest for India (Turchenko et al., 2009). The Cu–Pb–Zn deposits in the Aravalli–Delhi belt and the lower Himalayas rift zone correspond to metamorphosed VMS deposits (e.g., Saladipura; Rampura Agucha). A significant number of Cu (U) deposits that formed in rift and subduction environments occurred in the Singhbhum Shear Zone in the southern part of the Singhbhum Craton. In addition, the magmatic Cu–Mo deposits (e.g., Malanjkhand) are located at an extension of the Singhbhum Shear Zone (Sarkar and Deb, 1974; Pal et al., 2009; Shi et al., 2010). There are also a great number of small Cu, Cr, Fe, and W deposits in the Singhbhum Shear Zone and world-class lamproite diamond deposits in the marginal active belt in the Singhbhum Craton. The GOE resulted in the occurrence of shoal-water carbonate sedimentation and the development of strata-bound base-metal deposits. The Bhilwara Supergroup hosts Zn-Pb-Ag ore mineralization (Dariba–Raipur) related to Proterozoic ensialic foldbelts. Stratiform Pb-Zn deposits are localized in the carbonate part of a section in the Aravalli Supergroup (Deb, 1986; Höller et al., 1996; Turchenko et al., 2009). A large number of Mn (BIF) (e.g., Sadanandrapur), graphite (e.g., Chintakonda), and superimposed muscovite pegmatite deposits (e.g., Sangam) occurred in the belt of the Proterozoic tectonothermal reworking of the Eastern Ghats, which is an important ore-bearing tectonic unit that bears indications of polycyclic collision (Turchenko et al., 2009). The manganese deposits are hosted in the Khondalite Group. Stromatolitic limestone from the Deogiri Fm (lower part of Khondalite Group) yielded a well-fitted Pb–Pb isochron date of 2475 Ma, representing the time of metamorphic recrystallisation (Russell et al., 1996).

The metallogenesis in the Mesoproterozoic Era was related to Craton rifting. The ore deposits related to acidic magma at 1.66–1.55 Ga are vanadium–titanium–iron deposits (Kanyakumari) in the Singhbhum Craton (Sharma, 2009; Turchenko et al., 2009; Chatterjee et al., 2012). The Dharwar Craton Kuddapah Basin in the early Mesoproterozoic was rich in strata-bound Zn-Pb-Cu deposits and barite. Pb-Zn deposits are hosted in sedimentary rocks, whereas Cu mineralization is noted in basic volcanic rocks (Sarkar and Dasgupta, 1980; Panigrahi et al., 1993; Sarkar et al., 2000; Nagarajur et al., 2006; Turchenko et al., 2009).

3.3. Comparison between Precambrian metallogenesis of the NCC and the IND

Based on the dataset of typical deposits in the NCC and IND, a comparison of the evolution patterns of the Precambrian metallogenesis of the NCC and the IND is conducted (Fig. 4). Fig. 4 shows that the metallogenesis of the NCC was different from that of the IND during the Paleoarchaean, but they were comparable from the Mesoarchaean to the Mesoproterozoic. The results are briefly described as follows:

A (3600–3300 Ma): The paleo-continental nuclei formed and the continental crust rapidly grew. The ore deposits in the NCC were less singly diversified. Only BIF deposits occurred in the Caozhuang Group in the Jidong zone. In contrast, the ore deposits thrived in the IND. The major ore deposits are BIF, Cr, Cr (Ni-Co), Cu, Pb-Zn-Cu and magnesite, which are hosted in the Dharwar granulite-gneiss area. The regional metallogeny of the NCC differed from that of the IND during this period. The difference may be attributed to the intense tectonic evolution during the interval 3600–3300 Ma, as well as to the cratonization at 3000 Ma in Western Dharwar (Sharma, 2009), while the formation of paleo-continental nuclei and the fast growing of supracrustal rocks and granites in the NCC occurred at that time (Deng et al., 1999; Zhao et al., 2003b).

B (3300–2500 Ma): The continental crust grew rapidly and a large number of greenstone belts were developed. During 2600–2500 Ma, the micro-continental blocks were amalgamated and the cratonization was basically completed (Li et al., 2000; Kusky et al., 2007; Zhai, 2008; Shrama, 2009; Zhai, 2010; Zhai and Santosh, 2011). This period was a peak time for metallogenesis. The deposits of BIF, Au, and Pb-Zn-Cu in the NCC and the BIF-Mn, Au, Cu-Mo, and Pb-Zn-Cu deposits in the IND were

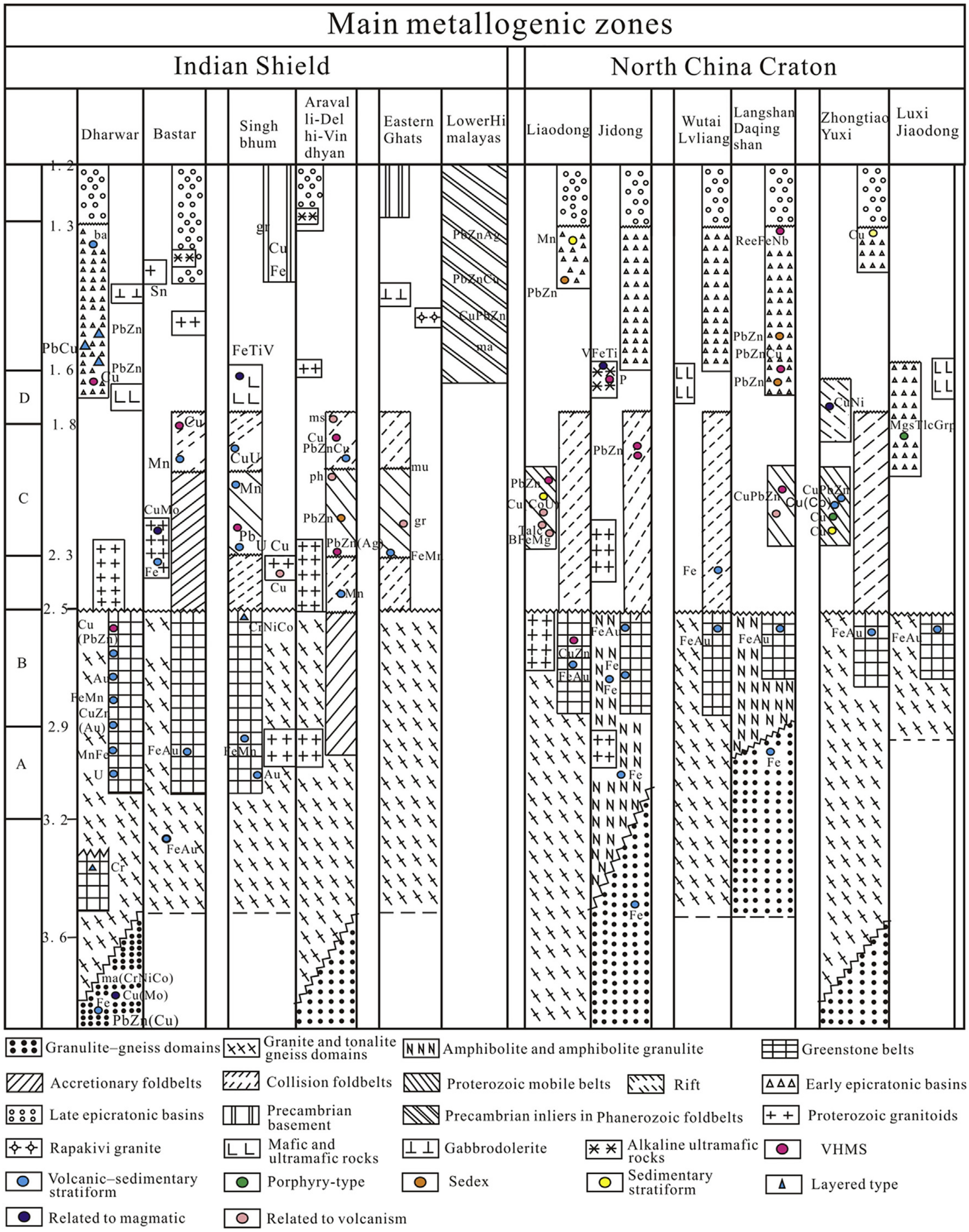

Figure 4. A comparison of the Precambrian metallogenesis between the North China Craton and the Indian Shield.

comparable. These deposits are all related to volcanic sedimentation (metamorphism) and are mostly distributed in greenstone belts and high-grade metamorphic zones.

C (2500–1800 Ma): The rifting–subduction–accretion-collision events occurred during Paleoproterozoic period, resulting in the emergence of active belts both in the NCC and the IND. Metallogenesis was controlled by active belts. The Cu–Pb–Zn metallogenic system in the NCC was comparable to that in the IND. In addition, the GOE led to the development of magnesite–boron–graphite deposits in the NCC, whereas Mn deposits were developed in large quantities in the IND.

D (1800–1400 Ma): After the cratonization of the NCC and the IND at ca. 1.85 Ga, multi-stage rifting events occurred in the late Paleoproterozoic to Neoproterozoic. The metallogenesis in the Mesoproterozoic was related to intracontinental rifts. The Pb-Zn-Fe metallogenic system in the NCC and the Pb-Zn-Cu-Fe metallogenic system in the IND were comparable. These Pb-Zn-Fe deposits are mostly related to anorogenic magmatism.

Table 3
Comparisons of major geological events and mineral systems between North China Craton and Indian Shield during Precambrian era.

Era (Ga)	North China Craton		Indian shield		References
	Major geological events	Major mineral systems	Major geological events	Major mineral systems	
>3.5	>3.5 Ga continental crust found in Anshan of north margin of North China, detrital zircon in Jidong gneiss, volcanic breccias in Henan Xinyang area, Yanchang Group of the north margin of Ordos Basin		∼3.5 Ga continental crust round in Bastar Sukma TTG gneiss, Markampura TTG gneiss, Babina TTG gneiss, Singhbhum OMTG gneiss		Goodwin, 1996; Zhao et al., 2003b; Liu et al., 2007; Zhai, 2010; Mohanty, 2012
3.4–2.9	Formation stage of North China continental nuclei with micro-continental block surrounding it, and rapidly growing supracrustal rocks and granite	BIF	Singhbhum amalgamation reached stability; Southern Indian TTG magmatic rocks and the protolith of granite grew rapidly	BIF; PGE; Cu Ni-Co-Cr;	Deng et al., 1999; Zhao et al., 2003b; Sharma, 2009; Zhai, 2010
2.9–2.6	Massive growth of continental crust, with predominantly lateral growth of greenstone belts and vertical growth of TTG	BIF	Fast growth of Dharwar crust in Southern India with a large area of greenstone belt developed	BIF	Li et al., 2000, 2001; Sharma, 2009; Li et al., 2010; Zhai, 2010
2.6–2.5	Micro-continental blocks were amalgamated; cratonization was basically completed; emergence of typical block tectonic system	BIF; Cu-Pb-Zn (VHMS); Au	Dharwar, Bastar and Singhbhum blocks in southern India were amalgamated; Aravalli blocks in northern India were amalgamated, and cratonization was basically completed	BIF; PGE; Au	Li et al., 2000; Kusky et al., 2007; Zhai, 2008, 2010; Sharma, 2009; Zhai and Santosh, 2011;
2.5–2.0	Orogenic granulite facies metamorphism rifting activities (volcanic sediment) in north-western margin, basic rock emplacement, granite emplacement, early development of cap rock after great oxidation events.	BIF-Mn; Pb-Zn-Cu	Bastar rifting in southern India, violent volcanic activities, serious granite emplacement, and development of volcanic-sedimentary sequence after great oxidation events	BIF-Mn; Pb-Zn-Cu	Zhao et al., 1993; Li et al., 2000; Zhai, 2004, 2010, 2011; Rao et al., 2005; Sharma, 2009; Mohanty, 2012; Zhai and Santosh, 2013
2.0–1.8	Reformation in north-western Craton (granite emplacement, shear tectonic deformation; collision between eastern and western areas; cratonization completed and involved in Columbia cycle		Collision between southern and northern continental blocks in India, Indian cratonization completed and involved in Columbia cycle		Mazumder et al., 2000; Zhao et al., 2001, 2002, 2003a; Zhai, 2010; Mohanty, 2012; Sanyal and Sengupta, 2012
1.8–1.6	Extensional tectonic development, violent rift system activities, development of basic dyke swarm and anorthosite-rapakivi granite emplacement.	Pb-Zn-Cu; V-Ti-Fe-P	Dharwar rapakivi granite emplacement in southern Indian with the development of basic dyke swarm.	Pb-Zn-Cu; V-Ti-Fe	Zhai, M.G., 2004; Zhang et al., 2007; Peng et al., 2008; Sharma, 2009; Mohanty, 2012
1.6–1.2	Cap rock sedimentation in North China at 1.6–1.4 Ga; development of typical two-peak magmatic activity in north margin of North China at 1.4–1.3 Ga; intense rift system activity		Bastar intracontinental rift system development at 1.6–1.4 Ga in southern India, development of cap rock sediment; a series of magmatic activities related to splitting occurred in south India at 1.5–1.35 Ga	Cu; Barite; REE	Zhang et al., 2007; Yang et al., 2011; Chatterjee et al., 2012; Mohanty, 2012

4. Discussion

4.1. Tectonic affinity of the NCC and the IND

The NCC and the IND have the most ancient rock records among rocks with similar lithological basement, and mostly consist of Archaean to Paleoproterozoic rocks, including TTG gneiss, granite, amphibolite rocks, greenschist, BIF, charnockite, calcareous silicate rock, and migmatite. The tectonic evolution of the NCC showed strong similarity with that of the IND from the Archaean to Mesoproterozoic (Zhao et al., 2003a). The details are shown in Table 3. A total of 476 samples of zircon U-Pb ages and 262 samples of zircon Sm-Nd ages from different parts of the NCC (Fig. 5b and c) (Kusky et al., 2007; Liu et al., 2007), as well as the synthesis of all available geochronological data from the Satpura mountains and the adjacent cratons of the IND, show similar patterns (Fig. 5a; Mohanty, 2012). The age probability peaks were at ∼3600 to 3500, ∼3300, ∼2720 to 2600, ∼2560 to 2500, ∼2450 to 2400, ∼2250 to 2100, 1750 to 1950, ∼1720 to 1600, and ∼1200 Ma, respectively. Among the foregoing, the notable ages are ∼3300, ∼2720 to 2600, ∼2560 to 2500, ∼2250 to 2100, 1750 to 1900, and ∼1720 to 1650 Ma, respectively. The distribution characteristics of the regional tectonic rock units indicate that: (1) a rapid accretion of TTG gneiss and granite occurred at ∼3300 Ma (Goodwin, 1996; Deng et al., 1999; Zhao et al., 2003a; Liu et al., 2007; Sharma, 2009; Zhai, 2010; Mohanty, 2012); (2) global continental crust growth occurred at 2720–2600 Ma (Li et al., 2000, 2001; Li et al., 2010; Zhai, 2010); (3) an amalgamation of micro-continental blocks of NCC and IND occurred at 2560–2500 Ma; (4) a series of intra-continental rifting–subduction events occurred at ∼2250–2100 Ma (Zhao et al., 1993; Li et al., 2000; Rao et al., 2005; Sharma, 2009; Zhai, 2010, 2011; Mohanty, 2012; Zhai, 2013); (5) the assembly of eastern and western blocks of NCC occurred at 1900–1800 Ma when north and south Indian blocks collided and cratonized, as part of the Columbia supercontinent (Zhao et al., 2001, 2003b, 2005; Kusky et al., 2007; Zhai, 2010; Mohanty, 2011, 2012; Meert, 2012; Sanyal and Sengupta, 2012); and (6) the anorogenic magmatic activity with the large-scale emplacement of mafic dyke swarms occurred at ∼1800–1650 Ma (Li et al., 2000; Roy, 2000a; Zhai, 2004; Zhang et al., 2007; Peng et al., 2008; Sharma, 2009; Mohanty, 2012).

A detailed examination of the Precambrian metallogenic histories of the IND and the NCC showed that they have metallogenic similarities (Table 3): (1) the Archaean BIF metallogenic system, the Paleoproterozoic Cu-Pb-Zn system within the active belts and the Mesoproterozoic stratiform Pb-Zn system related to multi-rifting all developed in the two blocks; (2) the diversity of ore types increased with decreasing ages, and metallogeny reached its peak between the NeoArchaean and Mesoproterozoic; (3) the lower metamorphism of mineral deposits and host rocks with decreasing ages, as well as the early Precambrian deposits were subjected to intense metamorphism and deformation; (4) the Precambrian minerals coexisted mostly with volcanic rocks, sedimentary rocks and granite sequences; (5) the spatial distribution of mineral deposits showed a regular pattern.

Note that the north margin of the NCC (NC) and the west margin of the IND (WI) have similarities in geological and metallogenic characteristics from the middle Archaean to the Mesoproterozoic (Fig. 6a, c). The middle Archaean 3.4–3.3 Ga Chentaigou Supracrustal rocks and orthogneisses in Liaodong in the "NC" showed

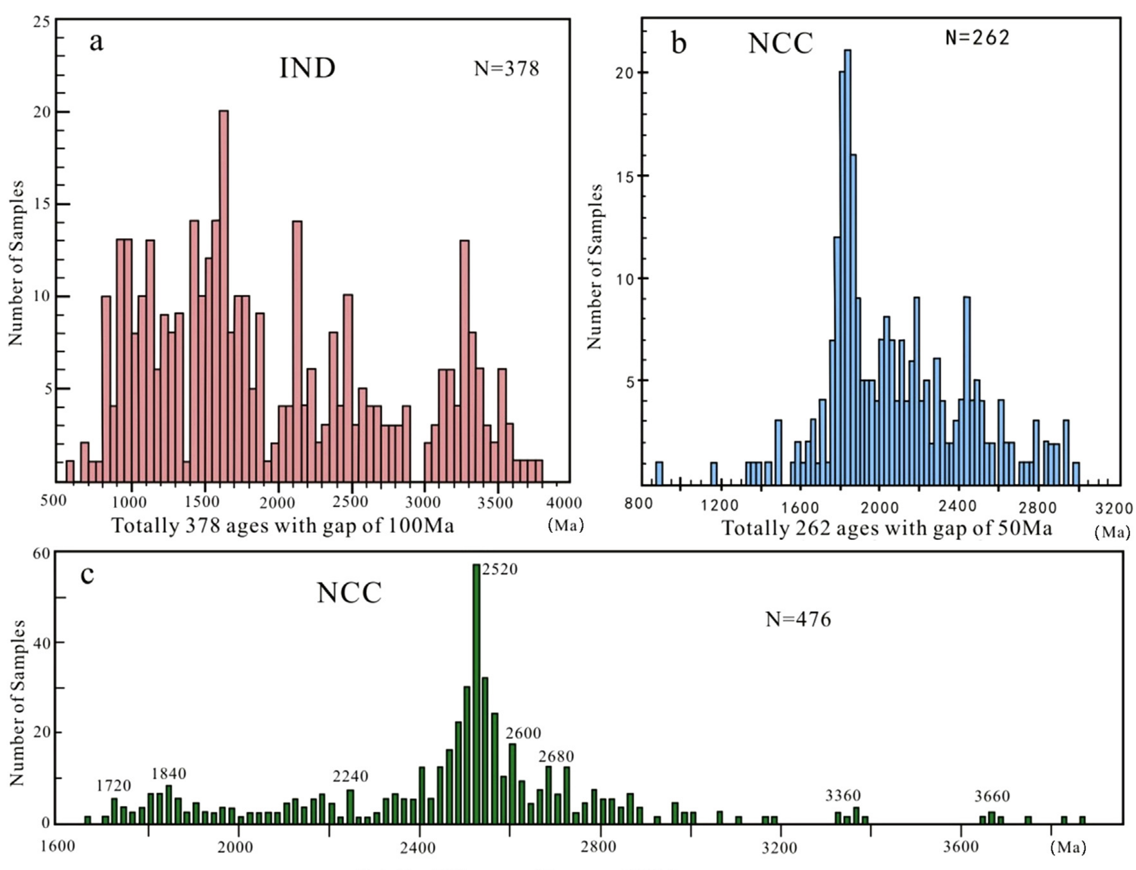

Figure 5. (a) Distribution of Precambrian age data from the Satpura mountains and adjoining cratons in the Indian Shield (from Mohanty, 2012); (b and c) distribution of Precambrian age data in the North China Craton (b–from Liu et al., 2007; c–from Kusky et al., 2007).

comparability with the 3.4–3.3 Ga Holenarsipur supracrustal rocks and Gorur gneiss in the Dharwar Craton in the "WI", respectively; and the 3.1–2.9 Ga Qian'an supracrustal rocks in Jidong in the "NC" are comparable to the 3.1–2.9 Ga Sargur Group in Dharwar Craton in the "WI" (Fig. 6b, d). The late Archaean Taishan Group in western Shandong in the eastern Block of the NCC showed comparability with the Dharwar Supergroup in the south Indian block (SIB). The Paleoproterozoic Liaohe Group in Liaodong in the "NC" can be comparable in gross aspects to the Singhbhum, Dhanjori and Kolhan Groups in SIB. The Changcheng Group and Jixian Group from Paleoproterozoic to Mesoproterozoic in the "NC" (>1400 Ma) showed comparability with the Cuddapah group and the Nallamalai Group in the SIB (Zhao et al., 2003a). In addition, with respect to metallogeny, the Archaean BIF-Au-Cu-Pb-Zn deposits in Liaodong in the "NC" showed comparability with those in the Dharwar Craton in the "WI". The deposits are distributed in the metamorphosed Archaean units and are interlayered with supracrustal volcano-sedimentary rocks in greenstone belts. During the Paleoproterozoic, active belts (e.g., Jiaoliao and Fengzhen active belt) and associated Pb-Zn-Mn deposits were developed in both the "NC" and "WI" (e.g., Aravalli-Delhi-Vindhyan belt). During the Mesoproterozoic, the deposits in the "NC" (Langshan-Daqingshan) and in the "WI" (Dharwar) were all dominated by stratiform Pb-Zn deposits associated with an extensional rifting environment induced by mantle upwelling. In addition, the Fe-Ti-V deposits in the central part of "NC" (Wutai-Lvliang) and those in the central part of "WI" (Singhbhum) were all related to anorogenic magmatism. Consequently, the "NC" showed comparability in metallogeny with the "WI", and thus the two regions might be connected during the middle Archaean to the Mesoproterozoic (Fig. 7a). Zhang et al. (2012) supported such connections in the northern hemisphere for the Columbia supercontinent based on high-quality paleomagnetic results from the ~1800 Ma Bundelkhand massif and the well-dated 1780 Ma Xiong'er Group in the southern NCC (Fig. 7c).

4.2. Implications of metasedimentary manganese metallogenesis

The Great Oxidation Event (GOE) occurred and resulted in a sharp increase of oxygen content during 2.35–2.0 Ga (Chen et al., 1996; Condie and Kröner, 2008). The Paleoproterozoic Mn-BIFs are regarded as a hallmark of the GOE (Condie and Kröner, 2008). Unfortunately, there are only minor volumes of Paleoproterozoic BIF in the NCC and the IND, and possible examples include the Yuanjiacun deposit in the Lanxian Group of the NCC and in the Bababudan area of the IND. However, the NCC and the IND both contain abundant metasedimentary manganese deposits during the late Archaean to the Paleoproterozoic (Roy, 2000b; Zhai, 2010). Experimental studies showed that photochemical oxidation of Mn^{2+} is inhibited in the presence of Fe^{2+} ions, and no firm evidence of biological oxidation of Mn^{2+} is recorded in the early Archaean (Anbar and Holland, 1992). Metasedimentary manganese deposits of small to moderate size are widespread in the Eastern Ghats belt in the IND. In contrast to the IND, the metasedimentary manganese deposits only occurred in the Dashiqiao Group in Liaodong, such as the very large Dashiqiao deposit. Moreover, the manganese

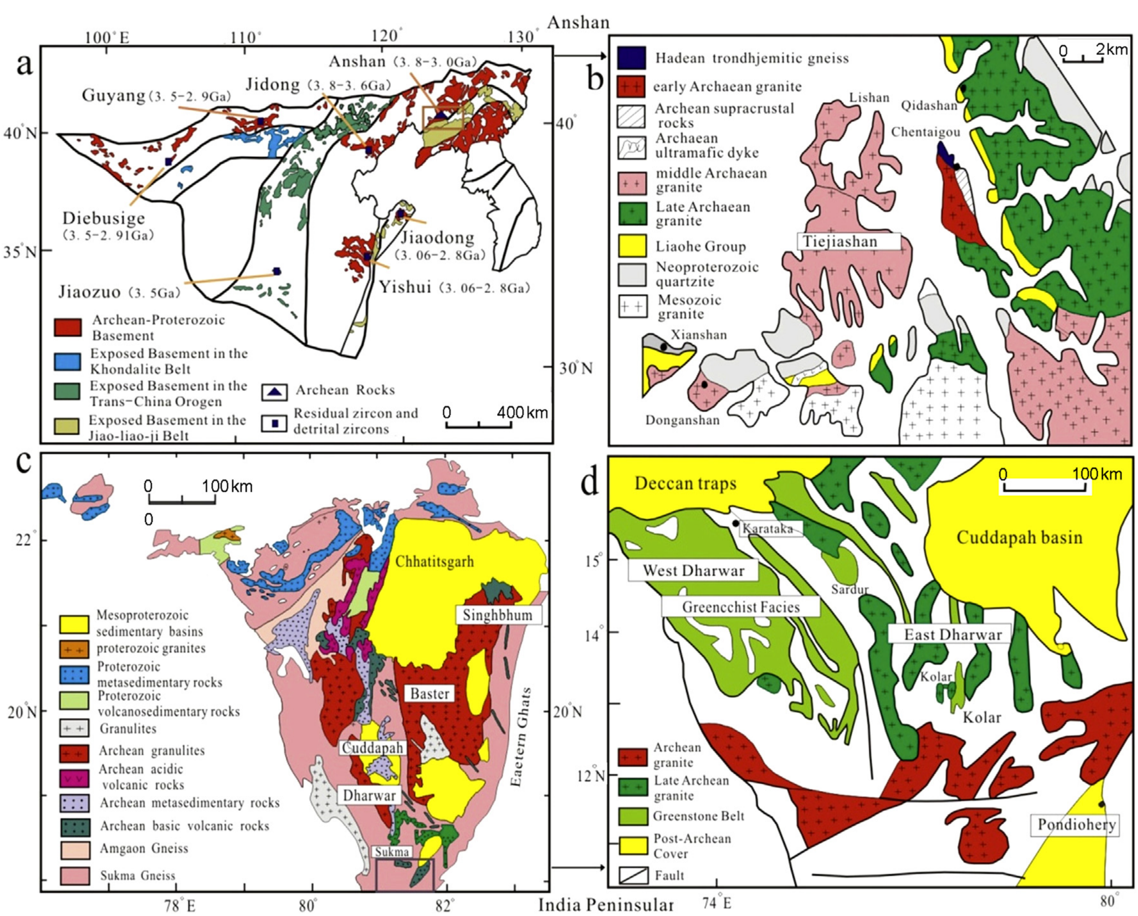

Figure 6. (a) A map of the North China Craton showing the locations where rocks and zircons are older than 2.8 Ga (revised after Liu et al., 2007); (b) regional distribution of early to late Archaean basement rocks in the Anshan area (revised after Zhao et al., 2003b); (c) geological units of the south of the Indian Shield (revised after Mohanty, 2012); (d) general geological sketch map of southern India showing the Peninsular gneisses, greenstone belts, late Archaean granulites and granitoids (revised after Zhao et al., 2003b).

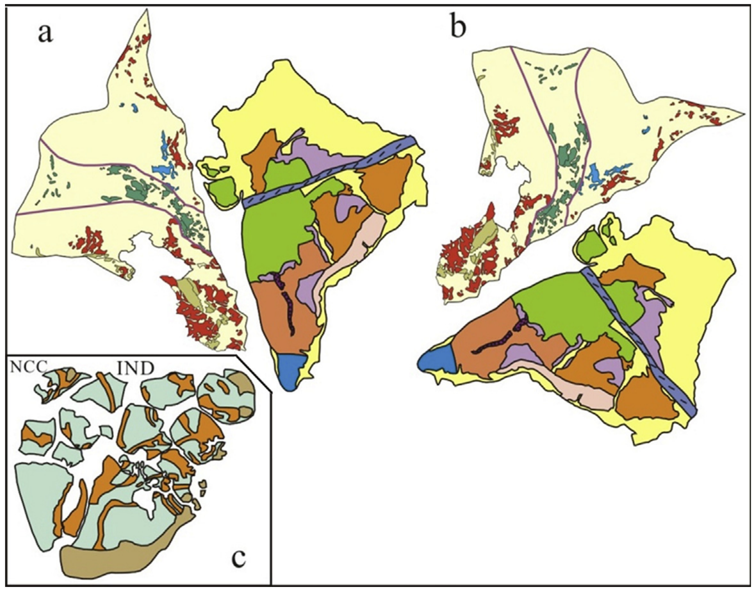

Figure 7. (a and b) Possible connection manners between northern margin of North China and western margin of India; (c) ~1740 Ma Columbia supercontinent (from Zhang et al., 2012).

deposits initiated at a modest scale in the IND during the late Archaean, which is earlier than that in the NCC where they occurred during the early Paleoproterozoic.

The appearance of metasedimentary manganese deposits promoted by possibly localized oxygenated environments in the shallow-water shelf are related to interactions of the atmosphere–hydrosphere system (Roy, 2000b). In the anoxic environment of the landward part of the fjord, Mn^{2+} was mobilized by reduction out of the clastic detrital materials. The Mn^{2+} was transported in solution to the ice-free parts of the fjord. Sharp intercalations of coarse-grained clastic sediments between the varve-like sedimented hematite-jaspilites and the bottom of the layered massive ore seams (Mn^{2+} to Mn^{4+}) indicate an episodic increase in the current velocities in the fjord prior to the precipitation of manganese oxides. Accelerated current velocities caused by increasing ice-melting rates of the glacier and in the hinterland resulted in an increasing supply of fresh, oxygen-rich water. As the oxidation potential increased, manganese oxides were precipitated. Lower ice-melting rates combined with a transgression of the glacier stopped the sedimentation of manganese ores (Fig. 8). Namely, a partly ice-covered condition after the "Ice earth" during 2.5–2.3 Ga was more favorable for precipitating manganese than the ice-covered condition because of a lack of exchange of oxygen between seawater and atmosphere under the ice cap of the glacier (e.g., Urban et al., 1992; Roy, 2000b; Condie and Kröner, 2008). Therefore, the IND and the NCC might be connected at low latitudes, where the condition was favorable for dissolving ice and precipitating manganese deposits. In contrast to the NCC, the IND was likely located at lower latitudes (Fig. 7b) in the northern hemisphere. That might explain why a larger amount of manganese deposits and earlier manganese metallogenesis occurred in the IND compared with the NCC.

5. Conclusions

Available lithostratigraphic, tectonothermal, geochronological, and paleomagnetic data for the NCC and the IND indicate that these two blocks have broad similarities from the middle Archaean to the Mesoproterozoic. The NCC and the IND went through three major tectonic cycles: (1) the Archaean massive growth of the continental crust and the amalgamation of micro-continental blocks, (2) a Paleoproterozoic intraplate rifting–subduction–accretion–collision with imprints of the GOE, and (3) Paleoproterozoic–Mesoproterozoic anorogenic magmatic activity. Three major metallogenic systems in the NCC and the IND corresponding to the major geological and tectonic events can also be recognized: the Archaean BIF metallogenic system, the Paleoproterozoic Cu–Pb–Zn metallogenic system, and the Mesoproterozoic Fe–Pb–Zn system. The similar metallogenesis from the middle Archaean to the Mesoproterozoic prove the tectonic affinity of the NCC and the IND.

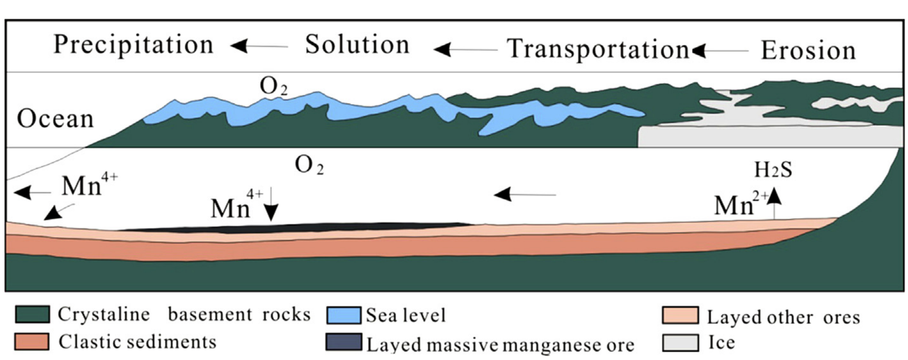

Figure 8. A model for the formation of manganese deposits during late Archaean (revised after Roy, 2000b).

The northern margin of the NCC (NC) showed strong similarities with the west margin of the IND (WI) in terms of geological and metallogenic features. The available geological and metallogenic data from the Eastern Block (Liaodong and Jidong) and active belts (Jiaoliao and Fengzhen) in "NC" fit those from the Dharwar craton and the Aravalli–Delhi–Vindhyan belt in "WI", respectively. Therefore, the "NC" and "WI" might have been connected from the middle Archaean to the Mesoproterozoic. In addition, the depositional model and environment of Paleoproterozoic metasedimentary manganese deposits implied that the assembly may have been located at low latitudes, where the conditions were favorable for the dissolution of ice after the "Ice Earth" (2.5–2.3 Ga) and the precipitation of a larger amount of manganese. The present work also brings new thinking and methods to the reconstruction of the supercontinent.

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